The collapse of WTC 2 caused the cellular phone system in Lower Manhattan to fail. However, there were still landlines working in the city blocks adjacent to the WTC site, and calls were still emanating from inside WTC 1.

All of the radio systems analyzed were working well just before the attack on the WTC. However, PAPD, FDNY, and NYPD were aware that radio communications had not fared well in high-rise buildings, including WTC 1 following the 1993 bombing. The vast amount of metal and steel-reinforced concrete in high-rise buildings was known to attenuate and block radio signals, especially the low output power emergency responder handie-talkies. This was again a problem on September 11, 2001, when all three agencies encountered difficulties with their hand-held units.

Thus, there was a heavy burden placed on the FDNY repeater to boost the weak signals to a discernable level. The repeater was functional during operations at the WTC; apparently the antenna was not damaged by debris from the aircraft impacts. However, within WTC 1, the system did not function correctly. The cause of this malfunction could not be determined since the unit was destroyed in the collapse of WTC 1. Repeater recording communications suggest that it was used within WTC 2. The radio recordings showed that communications readability using the repeater channel was generally good to excellent. Where readability levels were poor, it was generally caused by multiple people attempting to communicate over the radio at one time. The heavy traffic continued until the repeater failed with the collapse of WTC 2.

Had communications using the repeater been adequate in WTC 1, there would have been opposing effects on the quality of operations and life safety. On the positive side, the emergency personnel in the tower would have been in at least some contact with the Command Posts. However, two serious counterpoints would have occurred. First, if the responders in both towers were using the same repeater at the same time, the traffic would have been heavier, and more of the calls would have been indecipherable. Second, a firefighter in either tower would have had difficulty discerning which communications related to operations in his tower. Given the inadequate markings within the towers and the unfamiliarity of some emergency responders with the site, there was already a high degree of confusion as to which tower a responder was in.

The poor radio communications at the WTC had a serious impact on the FDNY Command Post's attempts to maintain command and control in general. All emergency responders struggled with the high volume and low quality of radio communications traffic at the WTC, described as "radio gridlock." NIST estimates that one-third to one-half of the emergency responder radio communications were undecipherable or incomplete.

The poor communications had a critical effect on the conveyance of evacuation instructions. As early as 8:48, there was an order to WTC personnel to clear WTC 1. At 8:59 a.m., a senior PAPD officer called for the evacuation of the two towers. At 9:01 a.m., this was extended to the entire complex. This was before the second aircraft struck. At 9:04 a.m., WTC Operations told people to evacuate an unidentified building. At 10:06 a.m., an NYPD aviation unit reported that it wouldn't be much longer before WTC 1 would come down. Some survivors reported not having received any of these messages. It is not known how many others did not, nor whether their locations were such that they could have made it out of the buildings in time.

7.2.6 The Overall Response

It was difficult to quantify the responders' degree of success. There were multiple reports of FDNY, NYPD, and PAPD efforts making the difference between death and survival. There were reports of assistance where the survival of the occupants was not determined. There were reports of firefighters quenching small fires on the lower floors of the towers and at the impact point in WTC 2. However, it would have been impossible for them to have had any significant effect on the fires that eventually led to the collapse of the structures.

7.3 FACTORS THAT CONTRIBUTED TO ENHANCED LIFE SAFETY

7.3.1 Aggregate Factors

- Reduced number of people in the buildings at the times of aircraft impact.
- Functioning elevators in WTC 2 for the 16 min prior to 9:02:59 a.m.
- Remoteness of Stairwell A from the impact zone and debris field.
- Participation of two-thirds of surviving occupants in recent fire drills.
- Upgrades to the life safety system components after the 1993 bombing.
- Evacuation assistance provided by emergency responders to evacuees.

7.3.2 Individual Factors

- Location below the floor of impact.
- Shortness of delay in starting to evacuate.

PART III: THE OUTCOME OF THE INVESTIGATION

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Chapter 8
PRINCIPAL FINDINGS

8.1 INTRODUCTION

This chapter presents the findings of the National Institute of Standards and Technology (NIST), organized according to the first three of the Investigation objectives for the World Trade Center (WTC) towers. The fourth objective is the subject of Chapter 9. WTC 7 is the subject of a companion report. The findings were derived from the extensive documentation summarized in the preceding chapters and described in detail in the accompanying reports. While NIST was not able to compile a complete documentation of the history of the towers, due to the loss of records over time and due to the collapses, the Investigators were able to acquire information adequate to support the findings and recommendations compiled in this chapter and the next. The chapter begins with summary statements and continues with the listing of the full set of principal findings.

8.2 SUMMARY

Objective 1: Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft.

- The two aircraft hit the towers at high speed and did considerable damage to principal structural components (core columns, perimeter columns, and floors) that were directly impacted by the aircraft or associated debris. However, the towers withstood the impacts and would have remained standing were it not for the dislodged insulation and the subsequent multi-floor fires. The robustness of the perimeter frame-tube system and the large size of the buildings helped the towers withstand the impact. The structural system redistributed loads in places of aircraft impact, avoiding larger scale damage upon impact. The hat truss, which was intended to support a television antenna atop each tower, prevented earlier collapse of the building core. In each tower, a different combination of impact damage and heat-weakened structural components contributed to the abrupt structural collapse.

- In WTC 1, the fires weakened the core columns and caused the floors on the south side of the building to sag. The floors pulled the heated south perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as the south wall buckled. The top section of the building tilted to the south and began its descent. The time from aircraft impact to collapse initiation was largely determined by how long it took for the fires to weaken the building core and to reach the south side of the building and weaken the perimeter columns and floors.

- In WTC 2, the core was damaged severely at the southeast corner and was restrained by the east and south walls via the hat truss and the floors. The steady burning fires on the east side of the building caused the floors there to sag. The floors pulled the heated east perimeter columns inward, reducing their capacity to support the building above. Their neighboring

columns quickly became overloaded as the east wall buckled. The top section of the building tilted to the east and to the south and began its descent. The time from aircraft impact to collapse initiation was largely determined by the time for the fires to weaken the perimeter columns and floor assemblies on the east and south sides of the building. WTC 2 collapsed more quickly than WTC 1 because there was more aircraft damage to the building core, including one of the heavily loaded corner columns, and there were early and persistent fires on the east side of the building where the aircraft had extensively dislodged insulation from the structural steel.

- The WTC towers would likely not have collapsed under the combined effects of aircraft impact damage and the extensive, multi-floor fires that were encountered on September 11, 2001, if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact.
- In the absence of structural and insulation damage, a conventional fire substantially similar to or less intense than the fires encountered on September 11, 2001, likely would not have led to the collapse of a WTC tower.
- NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers. Instead, photographs and videos from several angles clearly showed that the collapse initiated at the fire and impact floors and that the collapse progressed from the initiating floors downward, until the dust clouds obscured the view.

Objective 2: Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response.

- Approximately 87 percent of the estimated 17,400 occupants of the towers, and 99 percent of those located below the impact floors, evacuated successfully. In WTC 1, where the aircraft destroyed all escape routes, 1,355 people were trapped in the upper floors when the building collapsed. One hundred seven people who were below the impact floors did not survive. Because the flow of people from the building had slowed considerably 20 min before the tower collapsed, the stairwell capacity was adequate to evacuate the occupants on that morning.
- In WTC 2, before the second aircraft strike, about 3,000 people got low enough in the building to escape by a combination of self-evacuation and use of elevators. The aircraft destroyed the operation of the elevators and the use of two of the three stairways. Eighteen people from above the impact zone found a passage through the damaged third stairway (Stairwell A) and escaped. The other 619 people in or above the impact zone perished. Eleven people who were below the impact floors did not survive. As in WTC 1, shortly before collapse, the flow of people from the building had slowed considerably, indicating that the stairwell capacity was adequate that morning. It is presumed that the 11 people did not escape for the same reasons as the victims in WTC 1.

- About 6 percent of the survivors described themselves as mobility impaired, with recent injury and chronic illness being the most common causes; few, however, required a wheelchair. Among the 118 decedents below the aircraft impact floors, investigators identified seven who were mobility impaired, but were unable to determine the mobility capability of the remaining 111.

- A principal factor limiting the loss of life was that the buildings were one-third to one-half occupied at the time of the attacks. NIST estimated that if the towers had been fully occupied with 20,000 occupants each, it would have taken just over 3 hours to evacuate the buildings using the stairs and about 14,000 people might have perished because the stairwell capacity would not have been sufficient to evacuate that many people in the available time. Egress capacity required by current building codes is determined by single floor calculations that are independent of building height and does not consider the time for full building evacuation.

- Due to the presence of assembly use spaces at the top of each tower that were designed to accommodate over 1,000 occupants per floor for the Windows on the World restaurant complex and the Top of the World observation deck, the New York City (NYC) Building Code would have required a minimum of four independent means of egress (stairs), one more than the three that were available in the buildings. Given the low occupancy level on September 11, 2001, NIST found that the issue of egress capacity from these places of assembly, or from elsewhere in the buildings, was not a significant factor on that day. It is conceivable that such a fourth stairwell, depending on its location and the effects of aircraft impact on its functional integrity, could have remained passable, allowing evacuation by an unknown number of additional occupants from above the floors of impact. Moreover, if the buildings had been filled to their capacity with 20,000 occupants, the required fourth stairway would likely have mitigated the insufficient egress capacity for conducting a full building evacuation within the available time.

- Evacuation was assisted by participation in fire drills within the previous year by two-thirds of survivors and perhaps hindered by a Local Law that prevented employers from *requiring* occupants to practice using the stairways. The stairways were not easily navigated in some locations due to their design, which included "transfer hallways" where evacuees had to traverse from one stairway to another location where the stairs continued. Additionally, many occupants were unprepared for the physical challenge of full building evacuation.

- The functional integrity and survivability of the stairwells was affected by the separation of the stairwells and the structural integrity of stairwell enclosures. In the impact region of WTC 1, the stairwell separation was the smallest over the building height—clustered well within the building core—and all stairwells were destroyed by the aircraft impact. By contrast, the separation of stairwells in the impact region of WTC 2 was the largest over the building height—located along different boundaries of the building core—and one of three stairwells remained passable after the aircraft impact. The shaft enclosures were fire rated but were not required to have structural integrity under typical accidental loads—there were numerous reports of stairwells obstructed by fallen debris from damaged enclosures.

- The active fire safety systems (sprinklers, smoke purge, fire alarms, and emergency occupant communications) were designed to meet or exceed current practice. However, with the

exception of the evacuation announcements, they played no role in the safety of life on September 11 because the water supplies to the sprinklers were damaged by the aircraft impact. The smoke purge systems, operated under the direction of the fire department after the fires, were not turned on, but they also would have been ineffective due to aircraft damage. The violence of the aircraft impact served as its own alarm. In WTC 2, contradictory public address announcements contributed to occupant confusion and some delay in occupants beginning to evacuate.

- For the approximately 1,000 emergency responders on the scene, this was the largest disaster they had ever seen. Despite attempts by the responding agencies to work together and perform their own tasks, the extent of the incident was well beyond their capabilities. Communications were erratic due to the high number of calls and the inadequate performance of some of the gear. Even so, there was no way to digest, test for accuracy, and disseminate the vast amount of information being received. In the opinion of some first responders, communications and information sharing cost the lives of some emergency responders. Their jobs were complicated by the loss of command centers in WTC 7 and then in the towers after WTC 2 collapsed. With nearly all elevator service disrupted and progress up the stairs taking about 2 min per floor, it would have taken hours for the responders to reach their destinations, assist survivors, and escape before the towers collapsed.

Objective 3: Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1 and WTC 2.

- Because of The Port Authority of New York and New Jersey's (Port Authority's) establishment under a clause of the United States Constitution, its buildings were not subject to any state or local building regulations. The buildings were unlike any others previously built, both in their height and in their innovative structural features. Nevertheless, the actual design and approval process produced two buildings that generally were consistent with nearly all of the provisions of the NYC Building Code and other building codes of that time that were reviewed by NIST. The loads for which the buildings were designed exceeded the New York City code requirements. The quality of the structural steels was consistent with the building specifications. The departures from the building codes and standards identified by NIST did not have a significant effect on the outcome of September 11.

- For the floor systems, the fire rating and insulation thickness used on the floor trusses were of concern from the time of initial construction. NIST found no technical basis or test data on which the thermal protection of the steel was based. However, on September 11, 2001, the minimum specified thickness of the insulation was adequate to delay heating of the trusses and the amount of insulation dislodged by the aircraft impact was sufficient to enable the critical heating of the structural steel.

- Based on four standard fire resistance tests that were conducted under a range of insulation and test conditions, NIST found the fire rating of the floor system to vary between 3/4 hour and 2 hours; in all cases, the floors continued to support the full design load without collapse for over 2 hours.

- The wind loads used for the WTC towers, which governed the design of the external columns, significantly exceeded the requirements of the NYC Building Code and other building codes of the day that were reviewed by NIST. Two sets of wind load estimates for the towers obtained by independent commercial consultants in 2002, however, differed by as much as 40 percent. These estimates were based on wind tunnel tests conducted as part of insurance litigation unrelated to the Investigation.

The tragic consequences of the September 11, 2001, attacks were largely a result of the fact that terrorists flew large jet-fuel laden commercial airliners into the WTC towers. Buildings for use by the general population are not designed to withstand attacks of such severity; building regulations do not require building designs to consider aircraft impact. In our cities, there has been no experience with a disaster of such magnitude, nor has there been any in which the total collapse of a high-rise building occurred so rapidly and with little warning.

While there were unique aspects to the design of the WTC towers and the terrorist attacks of September 11, 2001, there are several possibilities to improve the safety of tall buildings, occupants, and emergency responders that result from this investigation of commonly used procedures and practices that were used in the design, construction, operation, and maintenance of the WTC towers. There also are possible improvements for selected buildings that owners may determine to be at higher risk due to their iconic status, critical function, or design. The recommendations in Chapter 9 suggest a variety of ways in which to achieve these safety improvements.

8.3 FINDINGS ON THE MECHANISMS OF BUILDING COLLAPSE

8.3.1 Summary of Probable Collapse Sequences

WTC 1 was struck by a hijacked aircraft at 8:46:30 a.m. and began to collapse at 10:28:22 a.m. WTC 2 was struck by a hijacked aircraft at 9:02:59 a.m. and began to collapse at 9:58:59 a.m. The specific factors in the collapse sequences relevant to both towers (the sequences vary in detail for WTC 1 and WTC 2) are:

- Each aircraft severed exterior columns, damaged interior core columns and knocked off insulation from steel as the planes penetrated the buildings. The weight carried by the severed columns was distributed to other columns.

- Subsequently, fires began to grow and spread. They were initiated by the aircraft's jet fuel, but were fed for the most part by the building contents and the air supply resulting from breached walls and fire-induced window breakage.

- These fires, in combination with the dislodged insulation, were responsible for a chain of events in which the building core weakened and began losing its ability to carry loads.

- The floors weakened and sagged from the fires, pulling inward on the exterior columns.

- Floor sagging and exposure to high temperatures caused the exterior columns to bow inward and buckle—a process that spread across the faces of the buildings.

- Collapse then ensued.

Seven major factors led to the collapse of WTC 1 and WTC 2:

- Structural damage from the aircraft impact;
- Large amount of jet fuel sprayed into the building interior, that ignited widespread fires over several floors;
- Dislodging of SFRM from structural members due to the aircraft impact, that enabled rapid heating of the unprotected structural steel;
- Open plan of the impact floors and the breaking of the partition walls by the impact debris that resulted in increased ventilation;
- Weakened core columns that increased the load on the perimeter walls;
- Sagging of the floors, that led to pull-in forces on the perimeter columns; and
- Bowed perimeter columns that had a reduced capacity to carry loads.

8.3.2 Structural Steels

- Fourteen different strengths of steel were specified in the structural engineering plans, but only 12 steels of different strength were actually used in construction due to an upgrade of two steels. Ten different steel companies fabricated structural elements for the towers, using steel supplied from at least eight different suppliers. Four fabricators supplied the major structural elements of the 9th to the 107th floors. Material substitutions of higher strength steels were not uncommon in the perimeter columns and floor trusses.
- About 87 percent of the tested steel specimens (columns, trusses and bolts) met or exceeded the required yield strengths specified in design documents. About 13 percent had NIST-measured strengths that were slightly lower than the design values, but this may have arisen from mechanical damage during the collapse, the natural variability of structural steel, and slight differences between the NIST and original mill test report testing protocols.
- The safety of the WTC towers on September 11, 2001, was most likely not affected by the fraction of steel that, according to NIST testing, was modestly below the required minimum yield strength. The typical factors of safety in allowable stress design were capable of accommodating the measured property variations below the minimum.
- The pre-collapse photographic analysis showed that 16 recovered exterior panels were exposed to fire prior to collapse of WTC 1. None of the nine recovered panels from within the fire floors of WTC 2 were observed to have been directly exposed to fire.
- None of the recovered steel samples showed evidence of exposure to temperatures above 600 °C for as long as 15 min. This was based on NIST annealing studies that established the

set of time and temperature conditions necessary to alter the steel microstructure. These results provide some confirmation of the thermal modeling of the structures, since none of the samples were from zones where such heating was predicted.

- Only three of the recovered samples of exterior panels reached temperatures in excess of 250 °C during the fires or after the collapse. This was based on a method developed by NIST to characterize maximum temperatures experienced by steel members through observations of paint cracking.

- Perimeter columns exposed to fire had a great tendency for local buckling of the inner web; a similar correlation did not exist for weld failure.

- Observations of the recovered steel provided significant guidance for modeling the damage from the aircraft impact with the towers.

- For the perimeter columns struck by the aircraft, fractures of the plates in areas away from a welded joint exhibited ductile behavior (necking and thinning away from the fracture) under very high strain rates. Conversely, fractures occurring next to a welded joint exhibited little or no ductile characteristics.

- There was no evidence to indicate that the type of joining method, materials, or welding procedures were improper. The welds appeared to perform as intended.

- The failure mode of spandrel connections on perimeter panels differed above and below the impact zone. Spandrel connections on exterior panels at or above the impact zone were more likely to fail by bolt tear out. For those exterior panels below the impact zone, there was a higher propensity for the spandrels to be ripped off from the panels. This may be due to shear failures as the weight of the building came down on these lower panels. There was no difference in failure mode for the spandrel connections whether the exterior panels were exposed to fire or not.

- With the exception of the mechanical floors, the perimeter panel column splices failed by fracture of the bolts. At mechanical floors, where splices were welded in addition to being bolted, the majority of the splices did not fail.

- Core columns failed at both splice connection and by fracture of the columns themselves.

- The damage to truss seats on perimeter panels differed above and below the impact zone in both towers. The majority of recovered perimeter panel floor truss connectors (perimeter seats) below the impact floors were either missing or bent downward. Above this level, the failure modes were more randomly distributed.

- In the floor trusses, a large majority of the electric resistance welds at the web-to-chord connections failed. The floor truss and the perimeter panel floor truss connectors typically failed at welds and bolts.

- The NIST-measured properties of the steels (strain rate, impact toughness, high-temperature yield and tensile strengths) were similar to literature values for other construction steels of the WTC era.
- The creep behavior of the steels could be modeled by scaling WTC-era literature data using room temperature tensile strength ratios.

8.3.3 Aircraft Impact Damage Analysis

- Both towers withstood the significant structural damage to the exterior walls, core columns, and floor systems due to the aircraft impact. WTC 2 was the more severely damaged building and the first to collapse. WTC 2 displayed significant reserve capacity, as evidenced by a post-impact rooftop sway that was more than one-third of that under the hurricane force winds for which the building was designed. The oscillation period of this swaying was nearly equal to that calculated for the undamaged structure. (Such an analysis was not possible for the less severely damaged WTC 1 due to the absence of equivalent video footage for the analysis.)
- American Airlines Flight 11 impacted the north wall of WTC 1 at a speed of 443 mph ± 30 mph, banked 25 degrees ± 2 degrees to the left (left wing downward) and with the nose tilted slightly downward. United Airlines Flight 175 impacted the south wall of WTC 2 at a speed of 542 mph ± 24 mph, banked 38 degrees ± 2 degrees to the left (left wing downward) and with the nose pointed slightly downward and to the right.
- The aircraft impact on WTC 1 caused extensive damage to the north wall of the tower, principally in the regions impacted by the fuselage, engine, and fuel-filled wing sections. Photographic evidence showed that 34 perimeter columns were completely severed, while four columns were heavily damaged, and two columns were moderately damaged.
- The impact simulations of WTC 1 indicated that three to six core columns were severed, and three to four columns were heavily damaged. The floor trusses, core beams, and floor slabs experienced significant impact-induced damage on floors 94 through 96, particularly in the path of the fuselage. The wing structures were fragmented at the exterior wall, and aircraft fuel was dispersed on multiple floors. Aircraft debris substantially damaged the nonstructural interior partitions and the workstations and dislodged insulation in its path. The bulk of the fuel and aircraft debris was deposited in floors 93 through 97 with the largest concentration on floor 94.
- The aircraft impact on WTC 2 caused extensive damage to the south wall of the tower and to the regions impacted by the fuselage, engine, and fuel-filled wing sections. Photographic evidence showed that 29 perimeter columns were completely severed, one was heavily damaged, and three were moderately damaged. Four perimeter columns on the north wall also were severed.
- The impact simulations of WTC 2 indicated that five to ten core columns were severed and up to four columns were heavily damaged. The rupture of some column splices on floors 77, 80, and 83 contributed significantly to the failure of the core columns. The floor trusses, core

beams, and floor slabs experienced significant impact-induced damage on floors 79 to 81, particularly in the path of the fuselage. The analyses indicated that the wing structures were fragmented due to the interaction with the exterior wall and, as a result, aircraft fuel was dispersed on multiple floors. The aircraft debris substantially damaged the building's contents and also dislodged insulation in its path. The bulk of the fuel was concentrated on floors 79, 81, and 82, while the bulk of the aircraft debris was deposited in floors 78 through 80, with the largest concentration on floor 80.

- Other effects of the aircraft impacts included (a) severing of the sprinkler and fire hose water supply systems, negating any possible fire suppression efforts; (b) dispersing of jet fuel and ignition of building contents over large areas; (c) increasing the air supply into the damaged buildings that permitted very large fires; and (d) damaging ceilings, enabling unabated heat transport to the floor structure above and over the floor-to-ceiling partition walls to the next compartment. These effects were consistent with photographic evidence and with the accounts of building occupants and emergency responders.

- The simulations fairly closely matched the exterior wall damage patterns from each of the aircraft impacts and correctly predicted the collapse of five of the six stairwell walls and the lesser damage to the sixth, the trajectories of the engine and wheels that penetrated the buildings, and the accumulation of furnishings and debris in the northeast corner of the 80th and 81st floors of WTC 2.

8.3.4 Reconstruction of the Fires

- In each tower, the fires were initiated simultaneously on multiple floors by ignition of some of the jet fuel from the aircraft. The initial jet fuel fires themselves lasted at most a few minutes.

- The principal combustibles on the fire floors were workstations. The total combustible fuel load on the WTC floors was about 4 lb/ft^2. Higher combusted fuel loadings resulted in slower fire spread rates that did not match the patterns observed in the photographic evidence. Under these higher combusted fuel loadings, the fires likely would not have reached the south side of WTC 1 in the time needed to cause inward bowing and collapse initiation.

- The aircrafts added significant combustible material to their paths (and the paths of their breakup fragments) through the buildings.

- It is possible to reconstruct a complex fire in a large building, even if the building is no longer standing. However, this requires extraordinary information to replace what might have been gleaned from an inspection of the post-fire premises. In the case of the WTC tower, this information included floor plans of the fire zones, burning behavior of the combustibles, simulations of damage to the building interior, and frequent photographic observations of the fire progress from the building exterior.

- The fires in WTC 1 were generally ventilation limited, i.e., they burned and spread only as fast as windows broke. Where the combustibles were not significantly relocated by the aircraft debris, they tended to burn out in about 20 min. This was consistent with the results

of workstation fire tests conducted by NIST, in which the fuel load was 4 lb/ft^2. Although there were multiple fires on some of the impact floors, the general trend was for the fires to move toward the south side of the tenant spaces.

- The fires in WTC 2 had sufficient air to burn at a rate determined by the properties of the combustibles. This was in large part due to the extensive breakage of windows in the fire zone by the aircraft impact. In contrast with WTC 1, there was little spread in WTC 2. The early fires persisted on the east side of the tower and particularly in the northeast corner of the 80th and 81st floors, where the aircraft debris had pushed a lot of fractured combustibles

- The Fire Dynamics Simulator can predict the room temperatures and heat release rate values for complex fires to within 20 percent, when the building geometry, fire ventilation, and combustibles are properly described.

- The Fire Structure Interface, developed for this Investigation, mapped the fire-generated temperature and thermal radiation fields onto and through layered structural materials to within the accuracy of the fire-generated fields and the thermophysical data for the structural components.

- Conventional office workstations reached a peak burning rate in about 10 min and continued burning for a total of about a half hour. Partial covering of surfaces with inert material reduced the peak burning rate proportional to the fraction covered, but did not affect the total amount of heat release during the entire burning.

- Jet fuel sprayed onto the surfaces of typical office workstations burned away within a few minutes. The jet fuel accelerated the burning of the workstation, but did not significantly affect the overall heat released.

- In the simulations, none of the columns with intact insulation reached temperatures over 300 °C. Only a few isolated truss members with intact insulation were heated to temperatures over 400 °C in the WTC 1 simulations and to temperatures over 500 °C in the WTC 2 simulations. In WTC 1, if the fires had been allowed to continue past the time of building collapse, complete burnout would likely have occurred within a short time since the fires had already traversed around the entire floor, and most of the combustibles would already have been consumed. In WTC 2, if the fire simulation were extended for 2 hours past the time of building collapse with all windows broken, the temperatures in the truss steel on the west side of the building (where the insulation was undamaged) would likely have increased for about 40 min before falling off rapidly as the combustibles were consumed. Temperatures of 700 °C to 760 °C were reached over approximately 15 percent of the west floor area for less than 10 min. Approximately 60 percent of the floor steel had temperatures between 600 °C and 700 °C for about 15 min. Approximately 70 percent of the floor steel had temperatures that exceeded 500 °C for about 45 min. At these temperatures, the floors would be expected to sag and then recover a portion of the sag as the steel began to cool. The temperatures of the insulated exterior and core columns would not have increased to the point where they would have experienced significant loss of strength or stiffness.

8.3.5 Structural Response and Collapse Analysis

- The core columns were weakened significantly by the aircraft impact damage and thermal effects. Thermal effects dominated the weakening of WTC 1. As the fires moved from the north to the south side of the core, the core was weakened over time by significant creep strains on the south side of the core. Aircraft impact damage dominated the weakening of WTC 2. With the impact damage, the core subsystem leaned to the southeast and was supported by the south and east perimeter walls via the hat truss and floors. As the core weakened, it redistributed loads to the perimeter walls through the hat truss and floors. Additional axial loads redistributed to the exterior columns from the core were not significant (only about 20 percent to 25 percent on average) as the exterior columns were loaded to approximately 20 percent of their capacity before the aircraft impact.

- The primary role of the floors in the collapse of the towers was to provide inward pull forces that induced inward bowing of perimeter columns (south face of WTC 1; east face of WTC 2). Sagging floors continued to support floor loads as they pulled inward on the perimeter columns. There would have been no inward pull forces if the floors connections had failed and disconnected.

- Column buckling over an extended region of the perimeter face ultimately triggered the global system collapse as the loads could not be redistributed through the hat truss to the already weakened building core. As the exterior wall buckled (south face for WTC 1 and east face for WTC 2), the column instability propagated to adjacent faces and caused the initiation of the building collapse. Perimeter wall buckling was induced by a combination of thermal weakening of the columns, inward pull forces from sagging floors, and to a much lesser degree, additional axial loads redistributed from the core.

- The WTC towers would likely not have collapsed under the combined effects of aircraft impact damage and the extensive, multi-floor fires that were encountered on September 11, 2001, if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact.

- In the absence of structural and insulation damage, a conventional fire substantially similar to or less intense than the fires encountered on September 11, 2001, likely would not have led to the collapse of a WTC tower.

- The insulation damage estimates were conservative as they ignored possibly damaged and dislodged insulation in a much larger region that was not in the direct path of the debris but was subject to strong vibrations during and after the aircraft impact. A robust criterion to generate a coherent pattern of vibration-induced dislodging could not be established to estimate the larger region of damaged insulation.

- For WTC 1, partitions were damaged and insulation was dislodged by direct debris impact over five floors (floors 94, 95, 96, 97, and 98) and included most of the north floor areas in front of the core, the core, and central regions of the south floor areas, and on some floors, extended to the south wall.

- For WTC 2, partitions were damaged and insulation was dislodged by direct debris impact over six floors (floors 78, 79, 80, 81, 82, and 83) and included the south floor area in front of the core, the central and east regions of the core, and most of the east floor area, and extended to the north wall.

- The adhesive strength of BLAZE-SHIELD D to steel coated with primer paint was found to be one-third to one-half of the adhesive strength to steel that had not been coated with primer paint. The SFRM products used in the WTC towers were applied to steel components with primer paint.

- The average thickness of the original thermal insulation on the floor trusses was estimated to be 0.75 in. with a standard deviation of 0.3 in. The average thickness of the upgraded thermal insulation was estimated to be 2.5 in. with a standard deviation of 0.6 in. Based on finite-element simulations, the thermal analyses for determining temperature histories of structural components used a thermally equivalent thickness of 0.6 in. and 2.2 in. for the original and upgraded insulation, respectively. For thermal analyses of the perimeter columns, spandrel beams, core beams, and core columns, the insulation on these elements was set to the specified thickness, due to a lack of field measurements.

- Based on four Standard Fire Tests conducted for various length scales, insulation thickness, and end restraints, the floor assemblies were shown to be capable of sagging without collapsing and supported their full design load under standard fire conditions for 2 hours or more without failure.

- For assemblies with a ¾ in. SFRM thickness, the 17 ft assembly's fire rating was 2 hours; the 35 ft assembly's rating was 1½ hours. This result raised the question of whether or not a fire rating of a 17 ft floor assembly is scalable to the longer spans in the WTC towers.

- The specimen with ½ in. SFRM thickness and a 17 ft span would not have met the 2 hour requirement of the NYC Building Code.

- There is far greater knowledge of how fires influence structures in 2005 than there was in the 1960s. The analysis tools available to calculate the response of structures to fires are also far better now than they were when the WTC towers were designed and built.

8.4 FINDINGS ON FACTORS AFFECTING LIFE SAFETY

8.4.1 Active Fire Protection

- Active fire protection systems for many buildings are designed to the same performance specifications, regardless of height, size, and threat profile.

- The active fire protection systems (alarms, suppression, and smoke purging) in the WTC towers were designed to meet or exceed then-current practice. However, the successful operation of these systems depended upon the fire threat being consistent with what had been anticipated based upon previous experience and best engineering practices of the day.

- The fire alarm systems in the towers provided for automatic fire detection, but required manual activation of notification devices. On September 11, 2001, the impact of the aircraft itself alerted occupants in the WTC buildings to the unfolding danger when the first aircraft hit.

- Soon after the first aircraft impact, an overwhelming number of alarms were displayed at the Fire Command Station in WTC 1. The alarm systems were only capable of determining and displaying (a) areas that had at some time reached alarm point conditions and (b) areas that had not. The quality and reliability of information available to emergency responders at the Fire Command Station was not sufficient to understand the fire conditions.

- Although the fire alarm systems used multiple communication path risers, the systems experienced performance degradation, especially in WTC 1 where all fire alarm notification and communication functions appear to have been lost above the floors of impact.

- There was no means at the Fire Command Stations to determine whether or not announcements reached and could be heard on the intended floors.

- Alarm systems store information that is valuable for understanding the fire and smoke development in a building, but no information from the fire alarm systems was located, and there was no indication that anyone looked for it during the cleanup of the WTC site. Survivability of alarm systems data on computer hard drives, memory modules, or printouts in building fires and collapse environments is not addressed in present installation standards.

- Transmission of critical data outside the building to a monitoring station would provide means to preserve event data.

- Except for specific areas that were exempted from required sprinkler coverage, sprinkler systems were installed throughout the towers. As designed, the water supplies (storage tanks and pumped city water), automatic sprinklers, and standpipe/pre-connected hose systems met or exceeded the applicable installation requirements in the NYC Building Code. There were other design features that were considered inconsistent with engineering best practices, but no evidence was found to indicate that these features affected the events that occurred on September 11.

- All the fires that occurred in sprinklered spaces in the towers prior to September 11, 2001, were controlled with three or fewer sprinklers, in some cases supplemented by manual fire fighting.

- On the floors where the major fires occurred on September 11, 2001, the sprinkler system played no part since their water supply was damaged by the aircraft impact. The typical sprinkler system was installed with one connection to the sprinkler riser, providing a single point of failure of the water supply to the floor level sprinklers.

- The sprinkler systems could have provided fire control at coverage areas up to two or three times the specified design area of 1,500 ft^2. However, 4,500 ft^2 constituted less than 15 percent of the area of a single floor in these buildings, and estimates of the extent of the

initial fires in WTC 1 and WTC 2 in 2001 were considerably greater than three times the specified design areas.

- There were redundant and sufficient supplies of water for the standpipe and sprinkler systems for control of normally expected fires on the floors where the September 11 fires occurred. Activating the secondary water supplies required manual operation of electric fire pumps by a sizable number of people at various locations.

- No information was available at the Fire Command Desk about the water supply in areas that were burning, leading to a Port Authority employee being sent up to assess the status.

- There was no information available regarding the performance of the non-aqueous fire suppression systems on September 11, 2001. The manually operated smoke purge systems were designed to be activated by the fire department after a fire was suppressed, and, therefore, were not initiated on September 11. It is unlikely the systems would have functioned as designed, due to loss of electrical power and damage to the HVAC shafts and other structural elements in the impact zone that were integral parts of the systems.

- Analysis indicated that the aircraft impact rupture of large return air shafts and related ductwork created a major path for vertical smoke spread in the towers.

8.4.2 Evacuation

- Approximately 87 percent of WTC occupants, and over 99 percent of those below the floors of impact, were able to evacuate successfully.

- At the time of the aircraft impacts, the towers were only about one-third to one-half occupied. Had they been at the full capacity of 20,000 workers and visitors per tower, computer egress modeling indicated that a full evacuation would have required just over 3 hours. Under those circumstances, about 14,000 occupants might have perished in the building collapses.

- There were 8,900 ± 750 people in WTC 1 at 8:46 a.m. on September 11, 2001. Of those, 7,470 (or 84 percent) survived, while 1,462 to 1,533 occupants died.[15] At least 107 occupants were killed below the aircraft impact zone. No one who was above the 91st floor in WTC 1 after the aircraft impact survived. This was due to the fact that the stairwells and elevators were destroyed and helicopter rescue was impossible.

- There were 8,540 ± 920 people in WTC 2 at 8:46 a.m. on September 11, 2001. Of those, 7,940 (or 93 percent) survived, while 630 to 701 occupants were killed.[15] Eleven of those killed were employed on floors located below the aircraft impact zone. Approximately 75 percent of the occupants above the 78th floor at 8:46 a.m. had successfully descended below the 78th floor prior to the aircraft impact at 9:03 a.m. The use of elevators and self-initiated evacuation during this period saved roughly 3,000 lives.

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[15] As shown in Table 4–1, there were a total of 71 decedents whose initial locations in the towers were not certain: 30 below the impact zone in either WTC 1 or WTC 2, 24 at an unknown location in WTC 1 or WTC 2, and 17 people for whom no location information was available.

- The evacuation from WTC 2 occurred in spite of conflicting announcements, first urging people to return to their offices around 9:00 a.m., and then informing them around 9:02 a.m. that they may initiate an evacuation if conditions warranted. A subsequent announcement at 9:20 a.m., after the second aircraft strike, informed occupants that they could use the Concourse if they wished to leave the building. An announcement at 9:37 a.m. instructed occupants to go down the stairs.

- Stairwell A in WTC 2 remained passable for at least some period of time after the aircraft impact because (1) only the end of the left wing, empty of jet fuel, was in line with the stairwell; (2) Stairwell A was behind the structural/architectural core in the area of impact; and (3) the aircraft debris had to travel through the longer dimension of the core and thus was slowed by a greater number of columns, shafts, walls, and mechanical equipment, and (4) Stairwell A was widely separated from Stairwells B and C.

- Eighteen people successfully used the debris-cluttered Stairwell A in WTC 2 to leave the building after being on or above the 78th floor when United Airlines Flight 175 hit the building. It is possible that additional occupants from above the impact floors were making their way down the stairwell some minutes before building collapse.

- Two-thirds of the WTC 1 occupants and half of the WTC 2 occupants had started working at the WTC in the previous 4 years.

- Two-thirds of the WTC 1 and WTC 2 occupants participated in at least one fire drill in the twelve months prior to September 11, 2001. Nearly all (93 percent) of these occupants were instructed about the location of the nearest stairwell. However, only half of the survivors had previously used a stairwell, in part since NYC Local Law 5 prohibited requiring occupants to practice stairwell evacuation.

- The NIST Investigation found no evidence that the occupants of WTC 1 heard public address system announcements, although the fire command station was attempting to make such announcements.

- The delays of about 5 min in starting evacuation were largely spent trying to obtain additional information, trying to make sense of the situation, and generally preparing to evacuate.

- People who started their evacuation on higher floors took longer to start leaving and substantially increased their odds of encountering smoke, damage or fire. These encounters, along with interruption for any reason, had a significant effect on increasing the amount of time that people spent to traverse their evacuation stairwell.

- The WTC occupants were inadequately prepared to encounter horizontal transfers during the evacuation process and were occasionally delayed by the confusion as to whether a hallway led to a stairwell and confusion about whether the transfer hallway doors would open or be locked.

- The WTC occupants were often unprepared for the physical challenge of full building evacuation. Numerous occupants required one or more rest periods during stairwell descent.

- In WTC 1, the average surviving occupant spent approximately 48 seconds per floor in the stairwell, about twice that observed in non-emergency evacuation drills. The 48 seconds does not include the time prior to entering the stairwell, which was often substantial. Some occupants delayed or interrupted their evacuation, either by choice or instruction.

- Downward traveling evacuees reported slowing of their travel due to ascending emergency responders, but this counterflow was not a major factor in determining the length of their evacuation time. Emergency responders reported trouble ascending the stairs because of the volume of evacuees in the stairwells.

- During the last 20 min before each building collapsed, the evacuation rate in each building had slowed to about one-fifth the immediately prior evacuation rate. This suggests that for those seeking and able to reach and use the undamaged exits and stairways, the egress capacity was adequate to accommodate survivors.

- Many opportunities to communicate important information in a timely manner were missed, such as the general location of the impact region or whether to evacuate or not. As a result, building occupants, 9-1-1 operators, fire department dispatch, WTC building officials, and Port Authority personnel lacked necessary information about the situation.

- Faced with an uncertain situation, occupants of both buildings received conflicting feedback / advice from a variety of sources (including 9-1-1 operators, FDNY, family and friends, and The Port Authority) regarding whether to evacuate, whether to break windows, and the nature of their situation. It is likely that, in many instances, the people giving advice had as little accurate information as those seeking it.

- The decision to establish the primary evacuation route underground through the Concourse and then up to street level near WTC 5 prevented a significant number of injuries and/or deaths.

- Approximately 1,000 surviving occupants had a limitation that impacted their ability to evacuate, including recent surgery or injury, obesity, heart condition, asthma, advanced age, and pregnancy. The most frequently reported disabilities were recent injuries and chronic illnesses. The fraction of occupants requiring use of a wheelchair was very small.

- Mobility-impaired occupants were not universally accounted for by existing evacuation procedures, as some were left by colleagues (later rescued by strangers), some in WTC 1 were temporarily removed from the stairwells in order to allow more able occupants to evacuate the building, and others chose not to identify their mobility challenge to any colleagues.

- Most mobility-impaired individuals were able to evacuate successfully, often with assistance from co-workers or emergency responders, and it is not clear how many were among the 118 from below the impact floors who did not survive. It does not appear that mobility-impaired individuals were significantly over-represented amongst the decedents. As many as 40 to 60 mobility-impaired occupants and their companions were found on the 12th floor of

WTC 1 by emergency responders. About 20 of these were making their way down the stairs shortly before the building collapsed. It is not known how many from this group survived.

- Due to the presence of assembly use spaces at the top of each tower that were designed to accommodate over 1,000 occupants per floor for the Windows on the World restaurant complex and the Top of the World observation deck, the NYC Building Code would have required a minimum of four independent means of egress (stairs), one more than the three that were available in the buildings. Given the low occupancy level on September 11, 2001, NIST found that the issue of egress capacity from these places of assembly, or from elsewhere in the buildings, was not a significant factor on that day. It is conceivable that such a fourth stairwell, depending on its location and the effects of aircraft impact on its functional integrity, could have remained passable, allowing evacuation by an unknown number of additional occupants form above the floors of impact. Moreover, if the buildings had been filled to their capacity with 20,000 occupants, the required fourth stairway would likely have mitigated the insufficient egress capacity for conducting a full building evacuation within the available time.

8.4.3 Emergency Response

- New York City's emergency responders had never experienced an operation of the size presented by the attack on the WTC. They typically followed their department policies and procedures for the operations they were required to carry out. Under these procedures, almost all emergency responder departments established their command posts within the potential collapse zone of the buildings.

- In general, all departments attempted to work together to save as many lives as possible. This was done with no formal structure of unified command between departments below the Commissioner level of operations.

- Unified operations were hindered by the FDNY and NYPD command posts being separated. Department Chiefs could not directly communicate with each other using their handie-talkies and did not formulate unified orders and directions for their departments. Neither FDNY nor NYPD had liaison officers working with the other department's command posts until after WTC 1 collapsed.

- The first emergency responders were colleagues and regular building occupants. Acts of individual heroism saved many people whom traditional emergency responders would have been unable to reach in time.

- The initial fire department assessment of the situation was correct regarding the general magnitude of damage, the status of the water supply, and the further limitations imposed on firefighting by the height of the impact. FDNY command personnel learned from 9-1-1 dispatch operators that smoke, fire, and structural damage in the buildings prevented many building occupants from evacuating floors above the impact zones. The decision was quickly made that fire department efforts should be directed toward evacuation and rescue of building occupants and should not focus on firefighting.

- Only one elevator in each building was of use to the responders. To gain access to the injured and trapped occupants, firefighters had to climb the stairs, carrying the equipment with them.

- NIST estimated that emergency responder climbing rates varied between approximately 1.4 min per floor for personnel not carrying extra equipment to approximately 2.0 min per floor for personnel wearing protective clothing and carrying extra equipment.

- Intense smoke and heat conditions on the top of the two WTC buildings prevented the NYPD helicopters from conducting roof evacuations.

- NYPD aviation unit personnel reported critical information about degrading building conditions before WTC 2 collapsed and critical information about the impending collapse of WTC 1 several minutes prior to its collapse. No evidence has been found to suggest that the information was further communicated to all emergency responders at the scene.

- There were roughly 1,000 emergency responders on the site. The Command Board approach to managing operations became overwhelmed with this large number of personnel and units reporting in for operations. The responding units generally followed good practices as related to accountability of staff. However, there were cases where individuals and ambulances did not report to the Command Posts. There was no way to locate or track units and individuals once they had departed to accomplish their tasks.

- Generally, the equipment used by the emergency responders was adequate for the operations being carried out. Flashlights were valuable, since the stairwells were generally dark and many areas were opaque with smoke and dust, especially in WTC 1 after the collapse of WTC 2. Self-contained breathing apparatus enabled responders to breathe when they were in the zones where the air was contaminated.

- For PAPD and NYPD, radio equipment did not appear to be a major problem during the operations. The PAPD's new radio antenna system provided it with a reasonable quality of radio communications until the collapse of WTC 2, at which time personnel were forced to switch to point-to-point communications. NYPD experienced successful operations with its radio equipment, mainly since only a few entered the WTC towers and the location of the mobilization point (a city block or more away from the towers) provided an unobstructed line of sight route for radio signals to enter and exit the building's windows.

- The overall emergency response was hampered by the loss of the Office of Emergency Management Command Center.

- The FDNY Incident Command Desk was hampered by the lack of a fully functional Field Communications unit, poor radio communications, and limited access to shared information critical to operations.

- The FDNY radio system was inadequate for locating and tracking the large number of personnel at the site. The FDNY relied heavily on hand-held units and knew that even the new handie-talkie radios did not work well in high-rise buildings where the signals were attenuated by the large amounts of metal and steel-reinforced concrete. Thus, the location of

Command Posts inside the buildings made calls to them subject to attenuation. Nonetheless, there were reports by emergency responders that their radios played a part in saving their lives.

- Radio communications overload quickly became a problem. After the first aircraft strike, there was a factor-of-five increase in emergency responder radio communications. This resulted in situations where the base station radio operators were unable to relay important information. Approximately 1/3 to 1/2 of the emergency radio communications were not complete messages or were not understandable.

- Communications within, from, and to WTC 1 were problematic. The building emergency communications system used to make the emergency announcements inside was inoperable as a result of the aircraft impact. The warden and standpipe phone systems were also not operating. The radio repeater in WTC 5, though found to be operational, was not effective in WTC 1. Eventually, only about half of the responders located in WTC 1 heard radio messages calling for the immediate evacuation of the building. Emergency responders who had the evacuation information told others.

- The WTC 5 repeater appeared to be effective in WTC 2. The Battalion Car Cross-band Repeater, recently developed by the FDNY and taken to the lobby of WTC 2, was used as a backup.

- Information overload led to an inability to pool and analyze information in real time and to distribute it to the emergency responders and the WTC occupants in a timely fashion. As a result, many emergency responders did not get the critical information they needed to maintain good situational awareness. Some occupants did not get information that potentially could have saved their lives, such as notification that Stairwell A was possibly passable from above the impact zone.

- A preponderance of evidence indicted that lack of timely information sharing and inadequate communication capabilities likely contributed to the loss of emergency responder lives.

- The collapse of WTC 2 totally disrupted the ongoing Incident Command System Operations being carried out by FDNY, NYPD, and PAPD.

- The private ambulances and Emergency Medical Service teams that responded to the WTC had limitations to their effectiveness. They had no protective clothing. They did not have the same radios, so the other agencies could not communicate with them. Only paper records were kept of patients being treated by official and self-dispatched emergency medical units. These records were lost when the buildings collapsed.

- Communications between the emergency response agencies and the media were problematic. Critical life safety and evacuation information from the WTC towers was not communicated to the news media so that it could be broadcast to people trapped inside the WTC towers above the building fires. By bypassing the appropriate emergency response agency contact points, some media firms interfered with the on-site operations.

8.5 FINDINGS ON OPERATIONAL CODES, STANDARDS, AND PRACTICES

8.5.1 General

- Although not required to conform to NYC codes, The Port Authority adopted the provisions of the proposed 1968 edition of the NYC Building Code, more than three years before it went into effect. The proposed 1968 edition allowed Port Authority to take advantage of less restrictive provisions and of technological advances compared with the 1938 edition, which was in effect when design for the WTC towers began in 1962.

- The NYC Department of Buildings reviewed the WTC tower drawings in 1968 and provided comments to The Port Authority concerning the plans in relation to the 1938 NYC Building Code. The architect-of-record submitted to The Port Authority responses to those comments, noting how the plans conformed to the 1968 NYC Building Code

- In 1993, The Port Authority and the NYC Department of Buildings entered into a memorandum of understanding that restated The Port Authority's longstanding policy to ensure that its facilities in the City of New York meet and, where appropriate, exceed the requirements of the NYC Building Code.

- The Port Authority was not required to yield, and appears not to have yielded, jurisdictional authority for regulatory and enforcement oversight to the New York City Department of Buildings. The Port Authority was created as an interstate entity, under a clause of the U.S. Constitution permitting compacts between states, and is not bound by the authority of any local or state jurisdiction.

- It was remarkable that the Investigation Team was able to obtain the large quantity of documentation of the construction and subsequent modification of the WTC towers. Such documents are normally not archived for more than about 6 years to 7 years, with no requirements for storage remote from the building. In the case of the WTC towers, The Port Authority and its contractors and consultants maintained an unusually comprehensive set of documents, a dominant portion of which had not been destroyed in the collapse of the buildings but was assembled and provided to the Investigation Team.

- The Architect of Record was responsible for specifying the fire protection and designing the evacuation system. There was not, and still is not, a requirement for a fire protection engineer to be part of the process. In the case of the WTC towers, the building owner played a significant role in specifying the fire protection and evacuation systems.

- The current state-of-practice is not sufficiently advanced for engineers to routinely analyze the performance of a whole structural system under a prescribed design-basis fire scenario.

- Buildings were not (and still are not) specifically designed to withstand the impact of fuel-laden commercial aircraft, and building codes in the United States do not require building designs to consider aircraft impact.

- While two documents from The Port Authority indicated that the safety of the WTC towers and their occupants in an aircraft collision was a consideration in the original design, it appears that the effect of the subsequent fires was not considered. NIST was unable to locate any documentary evidence on the aircraft impact analysis considered by The Port Authority.

8.5.2 Structural Safety

- At the time of the design and construction of the WTC towers, there were no explicit structural integrity provisions to mitigate progressive collapse. U.S. Federal agencies and the United Kingdom have since developed and implemented such guidelines. New York City adopted by rule in 1973 a requirement for buildings to resist progressive collapse under extreme local loads. The rules apply specifically to buildings that used precast concrete wall panels and not to other types of buildings.

- At the time of the design and construction of the WTC towers, there were no explicit minimum structural integrity provisions for the means of egress (stairwells and elevator shafts) in the building core that were critical to life safety. The building core, generally designed to be part of the vertical gravity load-carrying system of the structure, need not be part of the lateral load-carrying system of the structure. In this case, the structural designer may have preferred the use of partition walls rather than structural walls in the core area to reduce building weight. In the case of the WTC towers, the core had 2 hour fire-rated, gypsum partition walls with little structural integrity, and the core framing was required to carry only gravity loads. Had there been a minimum structural integrity requirement to satisfy normal building and fire safety considerations, it is conceivable that the damage to stairways, especially at the floors of impact, may have been less extensive.

- Wind loads were a major factor in the design of structural components that made up the frame-tube steel framing system. Building codes allow the determination of wind forces from wind tunnel tests for use in design, but there were not (and still are not) standards for conducting wind tunnel tests and for the methods used in practice to estimate design wind loads from test results. Results of two sets of wind tunnel tests conducted for the WTC towers in 2002 by independent commercial laboratories as part of insurance litigation, and voluntarily provided to NIST by the parties to the litigation, show up to 40 percent differences in resultant forces on the structures. There were also significant differences among various specified design wind speeds. Such disparities are indicative of the limitations associated with the current state of practice in wind engineering for tall buildings.

- The original design wind loads on the towers exceeded those established in the prescriptive provisions of the NYC Building Code from 1968 through 2001. These wind loads were also higher than those required by other selected building codes and the relevant model building code of the time. Note, however, that the approach in these codes was oversimplified, and as a result, these codes may not be applicable for super-tall building design.

- In the original design of the towers, the calculated drift (the maximum sway of the building) was significantly larger than what is currently used in practice. However, drift was not, and is not, a design factor prescribed in building codes.

- The demand/capacity ratios (DCRs) of the columns, estimated from the original WTC design loads, were in general close to those obtained under current wind design practice. The DCRs for over 99 percent of the floor trusses and beams were less than unity as they should have been. The safety of the WTC towers on September 11, 2001 was most likely not affected by the fraction of structural members for which the demand exceeded allowable capacity due to: (1) the factor of safety in the allowable stress design method, (2) the load redistribution capability of the steel structures, and (3) the towers having been subjected to lighter than routine live loads and minimal wind loads at the time of the attacks.

- Under a combination of the original WTC design dead and wind loads, tension forces were developed in the exterior walls of both towers. The forces were largest at the base of the building and at the corners. The Investigation showed that the DCRs for the exterior wall splice connections were less than 1.0.

- For the towers' resistance to shear sliding under wind loads, the factor of safety was between 10 and 11.5, while the factor of safety against overturning ranged from 1.9 to 2.7 for both towers.

- The period of natural building oscillations calculated from the reference global model of the WTC 1 matched well those determined from accelerometers located atop the tower. This lent credence to the global models of the towers.

8.5.3 Fire Safety

- By being consistent with the proposed 1968 edition of the NYC Building Code, rather than the requirements of the 1938 Code, the tower design:
  - Eliminated a fire tower[16] (also called a smoke-proof stairway) as a required means of egress;
  - Reduced the number of required stairwells from 6 to 3 (see discussion in Section 5.35) and the size of doors leading to the stairs from 44 in. to 36 in.;
  - Reduced the fire rating of the shaft walls in the building core from 3 hours to 2 hours; and
  - Permitted a 1 hour reduction in fire rating for all structural components (columns from 4 hours to 3 hours and floor framing members from 3 hours to 2 hours) by allowing the owner/architect to select Class 1B construction for business occupancy and unlimited building height.

Many of these allowances in the 1968 NYC Building Code are contained in current codes.

[16] A fire tower (also called a smoke-proof stair) is a stairway that is accessed through an enclosed vestibule that is open to the outside or to an open ventilation shaft providing natural ventilation that prevents any accumulation of smoke without the need for mechanical pressurization.

- In 1993, The Port Authority adopted a policy providing for implementation of fire safety recommendations made by local government fire departments after a fire safety inspection of a Port Authority facility and for the prior review by local fire safety agencies of fire safety systems to be introduced or added to a facility. Later that year, The Port Authority entered into an agreement with FDNY that reiterated the policy adopted by The Port Authority, recognized the right of FDNY to conduct fire safety inspections of Port Authority properties in the City of New York, provided guidelines for FDNY to communicate needed corrective actions to The Port Authority, ensured that new or modified fire safety systems are in compliance with local codes and regulations, and required third-party review of such systems by a New York State licensed architect or engineer.

- Compartmentation of spaces is a key building fire safety requirement to limit fire spread. The WTC towers initially had 1 hour fire-rated partitions separating tenants (demising walls) that extended from the floor to the suspended ceiling, not the floor above (the ceiling tiles were not fire rated). Over the years, these partitions were replaced with partitions that were continuous from floor to floor (separation wall), consistent with the 1968 NYC Building Code. Some partitions had not been upgraded by 1997, and a consultant recommended to The Port Authority that it develop and implement a survey program to ensure that the remediation process occurred as quickly as possible. It appears that with few exceptions, nearly all of the floors not upgraded were occupied by a single tenant. The Port Authority adopted guidelines in 1998 that required such partitions to provide a continuous fire barrier from top of floor to underside of slab.

- No technical basis was found for selecting the sprayed fire-resistive material (SFRM) used or its thickness for the large-span open-web floor trusses of the WTC towers. The assessment of the insulation thickness needed to meet the 2 hour fire rating requirement for the untested WTC floor system evolved over time:

  - In October 1969, The Port Authority directed the insulation contractor to apply 1/2 in. of insulation to the floor trusses.

  - In 1999, The Port Authority issued guidelines requiring that insulation be upgraded to 1 1/2 in. for full floors undergoing alterations.

  - Unrelated to the WTC buildings, an International Conference of Building Officials (ICBO) Evaluation Service report (ER-1244), re-issued June 1, 2001, using the same SFRM recommends a minimum thickness of 2 in. for "unrestrained steel joists" with "lightweight concrete" slab.

- There was no code provision that specifically required the conduct of a fire resistance test if adequate data did not exist from other building components and assemblies to qualify an untested building element. Instead, several alternate methods were permitted, with limited guidance on detailed procedures to be followed. Both the Architect of Record (in 1966) and the Structural Engineer of Record (in 1975) stated that the fire rating of the floor system of the WTC towers could not be determined without testing. NIST did not find evidence indicating that such a test was conducted to determine the fire rating of the WTC floor system. The Port Authority informed NIST that there are no such test records in its files.

- Neither the 1968 edition of the NYC Building Code, which was used in the design of the WTC towers, nor the 2001 edition of the code, adopted the "structural frame" requirement. Use of the "structural frame" approach, in conjunction with the prescriptive fire rating, would have required the floor trusses, the core floor framing, and perimeter spandrels in the WTC towers to be 3 hour fire-rated, like the columns for Class 1B construction in the 1968 NYC Building Code. This approach, which appeared in the Uniform Building Code (a model building code) as early as 1953, was carried into the 2000 International Building Code (one of two current model codes). The WTC floor system was essential to the stability of the building as a whole since it provided lateral stability to the columns and diaphragm action to distribute wind loads to the columns of the frame-tube system.

- There was, and is, no technical basis to establish whether the construction classification and fire rating requirements were risk-consistent with respect to the design-basis hazard and the consequences of that hazard. For tall buildings, the likely consequences of a given threat to an occupant on the upper floors are more severe than the consequences to an occupant on the first floor, especially considering more difficult access by firefighters and increased time required for stairwell evacuation. There were, and are, no additional categories for tall buildings, where different building classification and fire ratings requirements may be appropriate.

- There were no field application and inspection requirements to ensure that the as-built condition of the passive fire protection, such as SFRM, conformed to conditions found in fire resistance tests of building components and assemblies. This includes determination of whether the as-applied average insulation thickness and variability was thermally equivalent to the specified minimum fire proofing thickness. (Currently, the NYC Building Code and the IBC require inspection of the SFRM, although self-certification is becoming common. NFPA 5000 requires a quality assurance program.) In addition, requirements were not available for in-service inspections of passive fire protection during the life of the building. The adequacy of the insulation of the WTC towers posed an issue of some concern to The Port Authority over the life of the buildings.

- Structural design did not, and does not, consider fire as a design condition, as it does the effects of dead loads, live loads, wind loads, and earthquake loads. Current prescriptive code provisions are based on tests that provide *relative* ratings of fire resistance. These may be adequate for simple structures and for comparing the relative performance of structural components in more complex structures. The state-of-the-art did not enable evaluation of the actual performance (i.e., load-carrying capacity) in a real fire of the structural components, or the structure as a whole system, including the connections between components.

- The provisions that were used for the WTC towers did not require specification of a fire-rating requirement for connections separate from those for the connected elements. The Investigation Team was unable to determine the fire rating of a connection where the connected elements had different fire ratings, and whether the applied insulation achieved that rating.

- There was, and is, no technical basis to establish whether the minimum mechanical and durability related properties of SFRM were sufficient to ensure acceptable in-service

performance in buildings. This includes the ability of such materials to withstand typical shock, impact, vibration, or abrasion effects over the life of a building. There are now measurement methods for many of these properties, but the relationship of the results to serviceability requirements is in need of technical support.

- There were no validated tools to analyze the dynamics of building fires and their effects on the structural system that would have allowed engineers to evaluate structural performance under alternative fire scenarios and fire protection strategies. While considerable progress has been made in recent years, significant work remains to be done before adequate tools are available for use in routine practice. NIST had to further develop and validate tools to investigate the fire performance of the WTC towers.

- Building code provisions for sprinkler installation in office buildings were an option in lieu of compartmentation. NYC has since promulgated local laws to encourage installation of sprinklers in new buildings, and is now considering a law to require sprinklers in existing buildings. The WTC towers were fully sprinklered by 2001, about 30 years after their construction.

- Active smoke management systems and/or combination fire/smoke dampers were not required in fully sprinklered buildings by the 1968 NYC Building Code or any subsequent, retroactive provisions.

- With a few special exceptions, building codes in the United States did not, and do not, require the use of fire-protected elevators for routine emergency access by first responders or as a secondary method (after stairways) for full building evacuation of occupants in emergencies.

- Firefighters moving up the stairs did not significantly lengthen the average time evacuees spent in the stairways. However, the climbing rate of the firefighter was hampered by the presence and movement of the evacuees.

- The separation of the three stairwells in each tower exceeded the requirements of the 1968 NYC Building Code. On some floors, the separation distances were not as large as the current model building codes require, while on other floors, the separation distances significantly exceeded the provisions in those codes.

8.6 FUTURE FACTORS THAT COULD HAVE IMPROVED LIFE SAFETY

In the course of the Investigation, NIST and its contractors were aware that there were modern, emerging, or even imagined capabilities that could have increased the survival rate of those in the WTC towers, had they been in place on September 11, 2001. These are listed here, not posed as recommendations for implementation, but presented for completeness in the portrayal of the findings of the Investigation. NIST has not conducted studies to evaluate the degree to which building performance and human factors could have been improved on September 11, 2001, had the capabilities been available.

8.6.1 Building Performance Factors

- Thermal insulation that bonds more firmly to structural steel.
- Perimeter column and floor framing with greater mass to enhance thermal and buckling resistance.
- Improved compartmentation and stairwell enclosures.
- Thermally resistant window assemblies to limit the air supply and retard fire growth.
- Steels with improved high temperature properties, especially with regard to creep.
- Fire protected and structurally hardened elevators for use in occupant evacuation and responder access.

8.6.2 Human Performance Factors

- More accurate and reliable communications among emergency responders and building occupants.
- Better management of large-scale emergency incidents.
- Better evacuation training.
- Self-evacuation capability for the mobility impaired.

Chapter 9
RECOMMENDATIONS

9.1 BUILDING REGULATIONS

As described in Chapter 5, codes and standards for the design, construction, operation, and maintenance of buildings are the documents by which a society states its intent to provide public safety and functionality. In the United States, building and fire safety regulations, promulgated and enforced by state and local jurisdictions, are based on model codes developed by private sector organizations—the International Code Council (ICC) and the National Fire Protection Association (NFPA). At present (June 2005), all or parts of 45 states plus the District of Columbia use the ICC's *International Building Code,* while 36 states plus the District of Columbia use the ICC's *International Fire Code.* Similarly, NFPA's *National Electrical Code* is used in virtually all jurisdictions. With the exception of standards for manufactured housing, the federal government's role in determining specific codes is mandatory only for federally owned, leased, regulated, or financed facilities.

The model codes adopt by reference voluntary consensus standards that are developed by a large number of private sector standards development organizations (SDOs). The SDOs include NFPA, ASTM International, the American Society of Civil Engineers (ASCE), the American Institute of Steel Construction (AISC), the American Concrete Institute (ACI), and the American Forest & Paper Association (AF&PA). The processes used by these organizations are accredited by the American National Standards Institute (ANSI), which administers and coordinates the U.S. voluntary standardization and conformity assessment system.

In addition to standards and codes organizations, there are other key stakeholder groups that either are responsible for or influence the practices used in the design, construction, operation, and maintenance of buildings in the United States. These typically include organizations representing building owners and managers (e.g., Building Owners and Managers Association, Construction Industry Institute), real estate developers (e.g., Real Estate Board of New York), contractors (e.g., Associated General Contractors, Associated Builders and Contractors), architects (e.g., American Institute of Architects), engineers (e.g., National Society of Professional Engineers, Society of Fire Protection Engineers, Structural Engineering Institute, National Council of Structural Engineering Associations), suppliers, and insurers. These groups also provide training, especially as it affects the ability to implement code provisions in practice. Lack of adequate training programs can limit the usefulness or widespread acceptance of improved code provisions. Very few members of the general public and building occupants participate in this process.

The National Conference of States on Building Codes and Standards (NCSBCS)—a body of the National Governors Association and the Council of State Governments—includes members representing chief building regulatory officials of the states and local code officials from across the nation. While NCSBCS does not develop or implement building codes, it provides a national forum to discuss issues related to codes, standards, and practices that cut across jurisdictional boundaries.

The National Institute of Standards and Technology (NIST) is a nonregulatory agency of the U.S. Department of Commerce. *NIST does not set building codes or standards, but provides technical support to the private sector and to other government agencies in the development of U.S. building and fire practice, standards and codes.* NIST provides this support by conducting research which helps to form the technical basis for such practice, standards, and codes; disseminating research results to practicing professionals; having its staff participate on technical and standards committees; and, providing technical assistance to the building and fire safety communities.

Rigorous enforcement of building codes and standards by state and local agencies, well trained and managed, is critical in order for standards and codes to ensure the expected level of safety. Unless they are complied with, the best codes and standards cannot protect occupants, emergency responders, or buildings.

9.2 NIST'S RECOMMENDATIONS FOR IMPROVING THE SAFETY OF BUILDINGS, OCCUPANTS, AND EMERGENCY RESPONDERS

NIST conducted its building and fire safety investigation of the World Trade Center (WTC) disaster of September 11, 2001, under the authority of the National Construction Safety Team Act (15 USC 7301 et seq.). The National Construction Safety Team's final report is required by the Act to include recommendations that address (1) specific improvements to building standards, codes, and practices, (2) changes to, or the establishment of, evacuation and emergency response procedures, and (3) research and other appropriate actions needed to help prevent future building failures.

As part of its WTC Investigation, NIST is issuing 30 recommendations that identify specific improvements in the way buildings are designed, constructed, maintained, and used and in evacuation and emergency response procedures.

- NIST believes that these recommendations are both realistic and achievable within a reasonable period of time and that their implementation would make buildings safer for occupants and emergency responders in future emergencies.

- NIST strongly urges that immediate and serious consideration be given to these recommendations by the building and fire safety communities—especially designers, owners, developers, codes and standards development organizations, regulators, fire safety professionals, and emergency responders.

- NIST also strongly urges building owners and public officials to (1) evaluate the safety implications of these recommendations to their existing inventory of buildings, and (2) take the steps necessary to mitigate any unwarranted risks without waiting for changes to occur in codes, standards, and practices.

NIST has assigned top priority to work vigorously with these communities to ensure that there is a complete understanding of the recommendations and their technical basis and to provide needed technical assistance. As part of this effort, NIST will develop and maintain a web-based system with information on the status of NIST's recommendations that will be available to the public so that progress in implementing them can be tracked.

In formulating its recommendations from the WTC Investigation, NIST considered:

- The relevant commonly used procedures and practices[17] and established baseline performance for the buildings, evacuation, and emergency response;
- The performance on September 11, 2001, compared to the baseline performance;
- Findings related to building performance, evacuation and emergency response, and to procedures and practices used in the design, construction, operation, and maintenance of the buildings;
- Whether these findings relate to the unique circumstances surrounding the terrorist attacks of September 11, 2001, or to normal building and fire safety considerations (including evacuation and emergency response);
- Technical solutions that are needed to address potential risks to buildings, occupants, and emergency responders, considering both identifiable hazards and the consequences of those hazards; and
- Whether the risks apply to all buildings or are limited to certain building types (e.g., buildings that exceed a certain height and floor area or that employ a specific type of structural system), buildings that contain specific design features, iconic/signature buildings, or buildings that house critical functions.

The 30 recommendations resulting from the NIST Investigation were prepared by the Investigation Team with benefit of review by the National Construction Safety Team Advisory Committee and the public. These improvements are to be achieved both by complying with existing codes and through provisions that address new requirements. Table 9–1 (which follows the recommendations) shows a crosswalk between the recommendations in each of eight groups and three categories. The topics addressed in each group of recommendations are:

1. Increased structural integrity, including methods for preventing conditions that could result in progressive collapse (when a building or a significant portion of a building collapses due to disproportionate spread of an initial local failure), standardizing the estimation of wind loads that frequently govern the design of tall buildings, and enhancing the stability of tall buildings.

2. Enhanced fire endurance of structures, including the technical basis for determining construction classification and fire resistance ratings, improvements to the technical basis for standard fire resistance testing methods, adoption of the "structural frame" approach to fire resistance ratings, and in-service performance requirements and conformance assessment criteria for spray-applied fire-resistive materials.

3. New methods for designing structures to resist fires, including the objective of burnout without collapse, the development of performance-based methods as an alternative to current prescriptive

[17] While there were unique aspects to the design of the WTC towers and the terrorist attacks of September 11, 2001, the design, construction, operation, and maintenance of the WTC towers—and the emergency response to the WTC towers—were based on procedures and practices that were commonly used for normal conditions.

design methods, the development and evaluation of new fire-resistive coating materials and technologies, evaluation of the fire performance of conventional and high-performance structural materials, and elimination of technical and standards barriers to the introduction of new materials and technologies.

4. Improved active fire protection, including the design, performance, reliability, and redundancy of sprinklers, standpipes/hoses, fire alarms, and smoke management systems.

5. Improved building evacuation, including system designs that facilitate safe and rapid egress, methods for ensuring clear and timely emergency communications to occupants, better occupant preparedness for evacuation during emergencies, and incorporation of appropriate egress technologies.

6. Improved emergency response, including better access to the buildings and better operations, emergency communications, and command and control in large-scale emergencies.

7. Improved procedures and practices, including encouraging code compliance by nongovernmental and quasi-governmental entities, adoption and application of egress requirements in available code provisions for existing buildings, and retention and availability of building documents over the life of a building.

8. Education and training programs for fire protection engineers, structural engineers, architects, and building regulatory and fire service personnel.

Each recommendation has been assigned a number (1, 2, 3, etc.) for easy reference. *The numerical ordering does not reflect any priority.*

The three categories and their subdivisions (also included in Table 9–1) are:

- Responsible Community:
  - Professional practices
  - Provisions in standards, codes, and regulations
  - Adoption and enforcement of the provisions
  - Research and development or requiring further study
  - Education and training

- Affected Population of Buildings:
  - All tall buildings[18]; building owners and public officials will need to determine appropriate performance requirements for buildings that are at risk due to types of structural, fire safety, or egress systems used, location, use, historic/iconic status, nature of occupancy, etc.
  - Selected other buildings (buildings that are at risk due to types of systems used, location, use, historic/iconic status, nature of occupancy, etc.).
- Relation to the outcome on September 11, 2001:
  - If in place, could have changed the outcome on September 11, 2001
  - Would not have changed the outcome, yet is an important building and fire safety issue that was identified during the course of the Investigation

In its recommendations, NIST does *not* prescribe:

- Specific systems, materials, or technologies. NIST encourages competition among different systems, materials, and technologies *that can meet performance requirements.*
- Specific threshold levels. NIST believes that the responsibility for the establishment of threshold levels properly belongs in the public policy setting process, in which the standards and codes development process plays a key role.

Only a few of the recommendations call for new requirements in standards and codes. Most of the recommendations deal with improving an existing standard or code requirement, establishing a standard for an existing practice without one, establishing the technical basis for an existing requirement, making a current requirement risk-consistent, adopting or enforcing a current requirement, or establishing a performance-based alternative to a current prescriptive requirement.

9.2.1 Group 1. Increased Structural Integrity

The standards for estimating the load effects of potential hazards (e.g., progressive collapse, wind) and the design of structural systems to mitigate the effects of those hazards should be improved to enhance structural integrity.

Recommendation 1. **NIST recommends that: (1) progressive collapse be prevented in buildings through the development and nationwide adoption of consensus standards and code provisions, along with the tools and guidelines needed for their use in practice; and (2) a standard methodology be developed—supported by analytical design tools and practical design**

[18] NIST has found that the physiological impacts on emergency responders of climbing numerous (e.g., 20 or more) stories makes it difficult to conduct effective and timely firefighting and rescue operations in building emergencies without functioning elevators. Consideration and better knowledge of factors such as ladder height, physiological factors involving emergency responders and building occupants, use of working elevators, and installation and use of protected elevators could refine the currently used definition of tall buildings to include multiple threshold levels.

guidance—to reliably predict the potential for complex failures in structural systems subjected to multiple hazards.

a. Progressive collapse[19] should be prevented in buildings. The primary structural systems should provide alternate paths for carrying loads in case certain components fail (e.g., transfer girders or columns). This is especially important in buildings where structural components (e.g., columns, girders) support unusually large floor areas.[20] Progressive collapse is addressed only in a very limited way in practice and by codes and standards. For example, the initiating event in design to prevent progressive collapse may be removal of one or two columns at the bottom of the structure. Initiating events at multiple locations within the structure, or involving other key components and subsystems, should be analyzed commensurate with the risks considered in the design. The effectiveness of mitigation approaches involving new system and subsystem design concepts should be evaluated with conventional approaches based on indirect design (continuity, strength, and ductility of connections), direct design (local hardening), and redundant (alternate) load paths. The capability to prevent progressive collapse due to abnormal loads should include: (i) comprehensive design rules and practice guides; (ii) evaluation criteria, methodology, and tools for assessing the vulnerability of structures to progressive collapse; (iii) performance-based criteria for abnormal loads and load combinations; (iv) analytical tools to predict potential collapse mechanisms; and (v) computer models and analysis procedures for use in routine design practice. The federal government should coordinate the existing programs that address this need: those in the Department of Defense; the General Services Administration; the Defense Threat Reduction Agency; and NIST. *Affected Standards*[21]*:* ASCE-7, AISC Specifications, and ACI 318. These standards and other relevant committees should draw on expertise from ASCE/SFPE 29 for issues concerning progressive collapse under fire conditions. *Model Building Codes:* The consensus standards should be adopted in model building codes (i.e., the *International Building Code* and NFPA 5000) by mandatory reference to, or incorporation of, the latest edition of the standard. State and local jurisdictions should adopt and enforce the improved model building codes and national standards based on all 30 WTC recommendations. The codes and standards may vary from the WTC recommendations, but satisfy their intent.

b. A robust, integrated predictive capability should be developed, validated, and maintained to routinely assess the vulnerability of whole structures to the effects of credible hazards. This capability to evaluate the performance and reserve capacity of structures does not exist and is a significant cause for concern. This capability also would assist in investigations of building failure—as demonstrated by the analyses of the WTC building collapses carried out in this Investigation. The failure analysis capability should include all possible complex failure phenomena that may occur under multiple hazards (e.g., bomb blasts, fires, impacts, gas explosions, earthquakes, and hurricane winds), experimentally validated models, and robust tools for routine analysis to predict such failures and their consequences. This capability should be developed via a coordinated effort involving federal, private sector, and academic research organizations in close partnership with practicing engineers.

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[19] *Progressive collapse* (or *disproportionate collapse*) occurs when an initial local failure spreads from structural element to structural element resulting in the collapse of an entire structure or a disproportionately large part of it.

[20] While the WTC towers eventually collapsed, they had the capacity to redistribute loads from impact and fire damaged structural components and subsystems to undamaged components and subsystems. However, the core columns in the WTC towers lacked sufficient redundant (alternate) paths for carrying gravity loads.

[21] A full listing of the affected standards, including the complete names of these standards, is provided in Table 9-2, which is located following the recommendations.

<u>Recommendation 2.</u> NIST recommends that nationally accepted performance standards be developed for: (1) conducting wind tunnel testing of prototype structures based on sound technical methods that result in repeatable and reproducible results among testing laboratories; and (2) estimating wind loads and their effects on tall buildings for use in design, based on wind tunnel testing data and directional wind speed data. Wind loads specified in current prescriptive codes may not be appropriate for the design of very tall buildings since they do not account for building-specific aerodynamic effects. Further, a review of wind load estimates for the WTC towers indicated differences by as much as 40 percent from wind tunnel studies conducted in 2002 by two independent commercial laboratories. Major sources of differences in estimation methods currently used in practice occur in the selection of design wind speeds and directionality, the nature of hurricane wind profiles, the estimation of "component" wind effects by integrating wind tunnel data with wind speed and direction information, and the estimation of "resultant" wind effects using load combination methods. Wind loads were a major factor in the design of the WTC tower structures and were relevant to evaluating the baseline capacity of the structures to withstand abnormal events such as major fires or impact damage. Yet, there is lack of consensus on how to evaluate and estimate winds and their load effects on buildings.

a. Nationally accepted standards should be developed and implemented for conducting wind tunnel tests, estimating site-specific wind speed and directionality based on available data, and estimating wind loads associated with specified design probabilities from wind tunnel test results and directional wind speed data.

b. Nationally accepted standards should be developed for estimating wind loads in the design of tall buildings. The development of performance standards for estimating wind loads should consider (1) appropriate load combinations and load factors, including performance criteria for static and dynamic behavior, based on both ultimate and serviceability limit states, and (2) validation of wind load provisions in prescriptive design standards for tall buildings, given the universally acknowledged use of wind-tunnel testing and associated performance criteria. Limitations to the use of prescriptive wind load provisions should be clearly identified in codes and standards.

The standards development work can begin immediately to address many of the above needs. The results of those efforts should be adopted in practice as soon as they become available. The research that will be required to address the remaining needs also should begin immediately and results should be made available for standards development and use in practice. *Affected National Standard:* ASCE-7. *Model Building Codes:* The standard should be adopted in model building codes by mandatory reference to, or incorporation of, the latest edition of the standard.

<u>Recommendation 3.</u> NIST recommends that an appropriate criterion be developed and implemented to enhance the performance of tall buildings by limiting how much they sway under lateral load design conditions (e.g., winds and earthquakes). The stability and safety of tall buildings depend upon, among other factors, the magnitude of building sway or deflection, which tends to increase with building height. Conventional strength-based design methods, such as those used in the design of the WTC towers, do not limit deflections. The deflection limit state criterion, which is proposed here is in addition to the stress limit and serviceability requirement; it should be adopted either to complement the safety provided by conventional strength-based design or independently as an alternate deflection-based approach to the design of tall buildings for life safety. The recommended deflection limit state criterion is independent of the criterion used to ensure occupant comfort, which is met in current practice by limiting accelerations (e.g., in the 15 to 20 milli-g range). Lateral deflections, which already are limited in the design of tall buildings to

control damage in earthquake-prone regions, should also be limited in non-seismic areas.[22] *Affected National Standards:* ASCE-7, AISC Specifications, and ACI 318. *Model Building Codes:* The standards should be adopted in model building codes by mandatory reference to, or incorporation of, the latest edition of the standard.

9.2.2 Group 2. Enhanced Fire Endurance of Structures

The procedures and practices used to ensure the fire endurance of structures be enhanced by improving the technical basis for construction classifications and fire resistance ratings, improving the technical basis for standard fire resistance testing methods, use of the "structural frame" approach to fire resistance ratings, and developing in-service performance requirements and conformance criteria for sprayed fire-resistive materials.

Recommendation 4. **NIST recommends evaluating, and where needed improving, the technical basis for determining appropriate construction classification and fire rating requirements (especially for tall buildings)—and making related code changes now as much as possible—by explicitly considering factors including:[23]**

- **timely access by emergency responders and full evacuation of occupants, or the time required for burnout without partial collapse;**
- **the extent to which redundancy in active fire protection (sprinkler and standpipe, fire alarm, and smoke management) systems should be credited for occupant life safety;[24]**
- **the need for redundancy in fire protection systems that are critical to structural integrity;[25]**
- **the ability of the structure and local floor systems to withstand a maximum credible fire scenario[26] without collapse, recognizing that sprinklers could be compromised, not operational, or non-existent;**
- **compartmentation requirements (e.g., 12,000 ft^2 [(27)]) to protect the structure, including fire rated doors and automatic enclosures, and limiting air supply (e.g., thermally resistant window assemblies) to retard fire spread in buildings with large, open floor plans;**

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[22] Analysis of baseline performance under the original design wind loads indicated that the WTC towers would need to have been between 50 percent and 90 percent stiffer to achieve a typical drift ratio used in current practice for non-seismic regions, though not required by building codes. Limiting drift would have required increasing exterior column areas in lower stories and/or significant additional damping.

[23] The construction classification and fire rating requirements should be *risk-consistent* with respect to the *design-basis hazards* and the *consequences* of those hazards. The fire rating requirements, which were originally developed based on experience with buildings less than 20 stories in height, have generally decreased over the past 80 years since historical fire data for buildings suggests considerable conservatism in those requirements. For tall buildings, the likely consequences of a given threat to an occupant on the upper floors are more severe than the consequences to an occupant on the first floor or the lower floors. For example, with non-functioning elevators, both the time requirements are much greater for full building evacuation from upper floors and emergency responder access to those floors. It is not clear how the current height and areas tables in building codes consider the technical basis for the progressively increasing risk to an occupant on the upper floors of tall buildings that are much greater than 20 stories in height.

[24] Occupant life safety, prevention of fire spread, and structural integrity are considered separate safety objectives.

[25] The passive fire protection system (includes fireproofing insulation, compartmentation, and firestopping) and the active sprinkler system each provide redundancy for maintaining structural integrity in a building fire, should one of the systems fail to perform its intended function.

[26] A maximum credible fire scenario includes conditions that are severe, but reasonable to anticipate, conditions related to building construction, occupancy, fire loads, ignition sources, compartment geometry, fire control methods, etc., as well as adverse, but reasonable to anticipate operating conditions.

- **the effect of spaces containing unusually large fuel concentrations for the expected occupancy of the building; and**
- **the extent to which fire control systems, including suppression by automatic or manual means, should be credited as part of the prevention of fire spread.**

Adoption of this recommendation will allow building codes to distinguish the risks associated with different building heights, fuel concentrations, and fire protection systems. Research is needed to develop the data and evaluate alternative proposals for construction classifications and fire ratings. *Model Building Codes:* A comprehensive review of current construction classification and fire rating requirements and the establishment of a uniform set of revised thresholds with a firm technical basis that considers the factors identified above should be undertaken.[28]

<u>Recommendation 5.</u> **NIST recommends that the technical basis for the century-old standard for fire resistance testing of components, assemblies, and systems be improved through a national effort. Necessary guidance also should be developed for extrapolating the results of tested assemblies to prototypical building systems. A key step in fulfilling this recommendation is to establish a capability for studying and testing the components, assemblies, and systems under realistic fire and load conditions.**

This effort should address the technical issues listed below:[29]

a. Criteria and test methods for determining:
   - structural limit states, including failure, and means for measurement;
   - effect of scale of test assembly versus prototype application, especially for long-span structures that significantly exceed the size of testing furnaces;
   - effect of restraining thermal expansion (end-restraint conditions) on test results, especially for long-span structures that have greater flexibility;
   - fire resistance of structural connections, especially the fire protection required for a loaded connection to achieve a specified rating;[30]
   - effect of the combination of loading and exposure (time-temperature profile) required to adequately represent expected conditions;
   - the repeatability and reproducibility of test results (typically results from a single test are used to determine rating for a component or assembly); and

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[27] Or a more appropriate limit, which represents a reasonable area for active firefighting operations.

[28] The National Fire Protection Association (NFPA) 5000 model code and the International Building Code (IBC) both recognize the risks associated with different building heights and accepted changes in 2001 and 2004, respectively. Both model codes now require that buildings 420 feet and higher have a minimum 4 hour structural fire-resistance rating. The previous requirement was 2 hours. The change provides increased fire resistance for the structural system leading to enhanced tenability of the structure and gives firefighters additional protection while fighting a fire. While NIST supports these changes as an interim step, NIST believes that it is essential to complete a comprehensive review that will establish a firm technical basis for construction classification and fire rating requirements.

[29] The technical issues were identified from the series of four fire resistance tests of the WTC floor system and the review and analysis of relevant documents that were conducted as part of this Investigation.

[30] There is a lack of test data on the fire resistance ratings of loaded connections. The fire resistance of structural connections is not rated in current practice. Also, standards and codes do not provide guidance on fireproofing requirements for structural connections when the connected members have different fire resistance ratings.

- realistic ratings for structural assemblies made with materials that have improved elevated temperature properties (strength, modulus, creep behavior).

b. Improved procedures and guidance to analyze and evaluate existing data from fire resistance tests of building components and assemblies for use in qualifying an untested building element.

c. Relationships between prescriptive ratings and performance of the assembly in real fires.

Affected National and International Standards[31]: ASTM E 119, NFPA 251, UL 263, and ISO 834. *Model Building Codes:* The standards should be adopted in model building codes by mandatory reference to, or incorporation of, the latest edition of the standard.

Recommendation 6. **NIST recommends the development of criteria, test methods, and standards: (1) for the in-service performance of sprayed fire-resistive materials (SFRM, also commonly referred to as fireproofing or insulation) used to protect structural components; and (2) to ensure that these materials, as-installed, conform to conditions in tests used to establish the fire resistance rating of components, assemblies, and systems.** This should include:

- Improved criteria and testing methodology for the performance and durability of SFRM (e.g., adhesion, cohesion, abrasion and impact resistance) under in-service exposure conditions (e.g., temperature, humidity, vibration, impact, with/without primer paint on steel[32]) for use in acceptance and quality control. The current test method to measure the bond strength, for example, does not distinguish the cohesive strength from the tensile and shear adhesive strengths. Nor does it consider the effect of primer paint on the steel surface. Test requirements that explicitly consider the effects of abrasion, vibration, shock, and impact under normal service conditions are limited or do not exist. Also, the effects of elevated temperatures on thermal properties and bond strength are not considered in evaluating the performance and durability of SFRM.

- Inspection procedures, including measurement techniques and practical conformance criteria, for SFRM in both the building codes and fire codes for use after installation, renovation, or modification of all mechanical and electrical systems and by fire inspectors over the life of the building. Existing standards of practice (AIA MasterSpec and AWCI Standard 12), often required by codes for some buildings need to be broadly applied to both new and existing buildings. These standards may require improvements to address the issues identified in this recommendation.

- Criteria for determining the effective uniform SFRM thickness—thermally equivalent to the variable thickness of the product as it actually is applied—that can be used to ensure that the product in the field conforms to the near uniform thickness conditions in the tests used to establish the fire resistance rating of the component, assembly, or system. Such criteria are needed to ensure that the as-installed SFRM will provide the intended performance.

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[31] While the WTC recommendations are focused mainly on U.S. national standards, each U.S. standard has counterpart international standards. In a recent report (ISO/TMB AGS N 46), the International Organization for Standardization (ISO), through its Advisory Group for Security (AGS), has recommended that since many of the ISO standards for the design of buildings date to the 1980s, they should be reviewed and updated to make use of the studies done by NIST on the World Trade Center disaster, the applicability of new technology for rescue from high buildings, natural disasters, etc. ISO's Technical Advisory Group 8 coordinates standards work for buildings.

[32] NIST tests showed that the adhesive strength of SFRM on steel coated with primer paint was a third to half of the adhesive strength on steel that had not been coated with primer paint. The SFRM products used in the WTC towers were applied to steel components coated with primer paint.